(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
15 March 2001 (15.03.2001)

PCT

(10) International Publication Number
WO 01/18885 A1

(51) International Patent Classification[7]: H01L 39/14

(21) International Application Number: PCT/GB00/03481

(22) International Filing Date: 11 September 2000 (11.09.2000)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
9921354.8 9 September 1999 (09.09.1999) GB

(71) Applicant (*for all designated States except US*): **CAMBRIDGE UNIVERSITY TECHNICAL SERVICES LTD.** [GB/GB]; The Old Schools, Trinity Lane, Cambridge CB2 1TS (GB).

(72) Inventors; and
(75) Inventors/Applicants (*for US only*): **GLOWACKI, Bartlomiej, Andrzej** [GB/GB]; IRC in Superconductivity, University of Cambridge, Madingley Road, Cambridge CB3 0HE (GB). **MAJOROS, Milan** [SK/GB]; IRC in Superconductivity, University of Cambridge, Madingley Road, Cambridge CB3 0HE (GB).

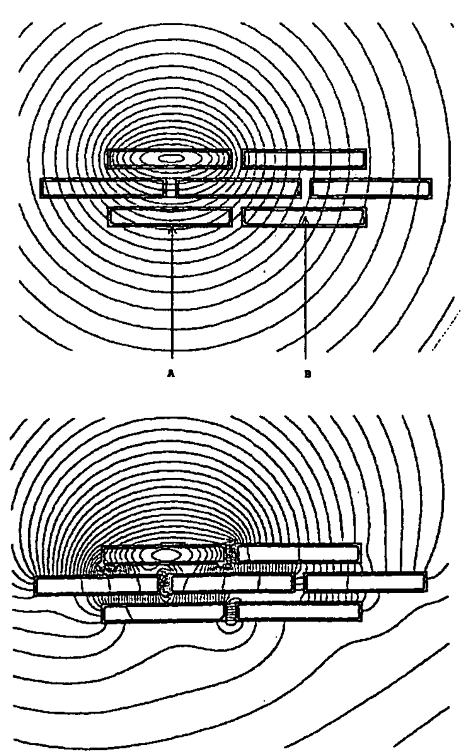
(74) Agent: **GILL JENNINGS & EVERY**; Broadgate House, 7 Eldon Street, London EC2M 7LH (GB).

(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CR, CU, CZ, DE, DK, DM, DZ, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.

(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian

[Continued on next page]

(54) Title: MULTIFILAMENTARY SUPERCONDUCTORS WITH MAGNETIC SCREENING LAYERS



a

b

(57) Abstract: Transport ac losses in multifilamentary superconductors are reduced by magnetic de-coupling of the filaments using magnetic screening. Any increase of the losses in the superconducting filaments caused by the presence of the magnetic material and the losses in the magnetic material itself, and any reduction of the transport current, are minor in comparison with reduction of ac losses. This reduction is more pronounced if the number of filaments is high. Individual filaments (B) comprising BSCCO, YBCO or the like are covered with a thin layer (A) of Fe or NiFe.

WO 01/18885 A1

WO 01/18885 A1

patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published:

— *With international search report.*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

MULTIFILAMENTARY SUPERCONDUCTORS WITH MAGNETIC SCREENING LAYERS

Field of the Invention

This invention relates to multifilamentary superconductors.

Background of the Invention

One of the most important parameters of multifilamentary superconductors, as wires or tapes, for from the point of view of their use in electrical energy transport, is their transport ac losses (so-called self-magnetic field losses or self-field losses). Both low-T_c and high-T_c wires and tapes can be treated as mono-core superconductors [1 - 6] because of filament coupling.

Several methods have been proposed, to isolate the filaments in multifilamentary superconductors, with special emphasis on (BiPb)SrCaCuO-2223 multifilamentary tapes [7 - 14]. The methods are based on increasing the matrix resistivity of the tapes by alloying Ag with e.g. Mg or Au [7, 8], twisting the filaments or on embedding them in an electrically insulating oxide barrier (e.g. $BaZrO_3$, $SrZrO_3$ or $SrCO_3$) or combining these two methods, i.e. twisting the filaments surrounded by the oxide barriers [9 - 12]. Alternative methods shield the (BiPb)SrCaCuO-2223 tape by deposition of a $Y_1Ba_2Cu_3O_{7-x}$ thin film onto its surface [13] or involve wrapping [14], in which thin and non-twisted (BiPb)SrCaCuO-2223 tapes are wrapped helically around a core wire, and where over-wrapping and/or plural-wrapping for each layer may transpose the filaments in such a composite.

It was found experimentally that while most of these methods are successful in decreasing the ac losses in (BiPb)SrCaCuO-2223 tapes exposed to an external ac magnetic field [9, 11], they are not effective in decreasing the transport ac losses, i.e. the self-field losses [4]. The self-field losses of (BiPb)SrCaCuO-2223 tapes, regardless of whether they have a high resistivity matrix, oxide barriers around the filaments or twisted filaments, still scale with the theoretical relations for a mono-core superconductor [4, 11]. This proves that, in self-field conditions, the filaments in (BiPb)SrCaCuO-2223 tapes are still magnetically coupled. The same is valid also for self-field losses in classical low-T_c superconductors [1]. To de-couple the filaments magnetically, quite large separation is needed, much larger than their dimensions [15,16]. Such separation greatly decreases the current-carrying capacity of the composite.

Summary of the Invention

According to the present invention, in order to de-couple the filaments magnetically, they are surrounded by a suitable low-loss ferromagnetic material. Such a magnetic de-coupling of the filaments can also be an effective technique to reduce ac losses of the multifilamentary superconductors exposed to moderate ac or dc external magnetic fields.

The invention utilises the shielding effect of magnetic material. The magnetic field of a current-carrying filament embedded in a ferromagnetic material propagates outside and is screened by ferromagnetic coverings of the neighbouring filaments, with the intention that the current distribution of the filaments inside these ferromagnetic coverings remains unaffected by the magnetic field of the current-carrying filament.

Brief Description of the Drawings

Fig. 1 shows the magnetic field lines (scale 2 x 10^{-8} Wb) of a model system of (6+1) filaments A each embedded in a ferromagnetic layer B of rectangular cross-section with: a) μ_r=1, b) μ_r=1000.

Fig. 2 shows the magnetic field lines (scale 6 x 10^{-10} Wb) of a model coated conductor with (6+1) filaments A embedded in a ferromagnetic layer B of rectangular cross-section, when current passes through the central filament only, for six (a - f) different combinations of values μ_r for the layer B, substrate C and buffer layer D.

Fig. 3 shows hysteretic loops for ferrite (F) and soft iron (S).

Fig. 4 shows the DC current-voltage characteristics of Sample 1 (see the Example): ▲, △ - bare tape, •, ○ - covered with Fe powder, ▼, ▽ - after removing Fe covering (solid symbols - increasing current, open symbols -decreasing current), a) linear scale, b) log-log scale.

Fig. 5 shows the normalized transport ac losses Q of Sample 1 in dependence on normalised current of amplitude I_0: a) measured by the potential wires C (•, ○) and E (■, □), (open symbols - Fe covered tape, solid symbols - bare tape); b) measured by the potential wires L (□ - bare tape, • - Fe covered, □ - Fe removed). (The solid and dashed lines represent the theoretical dependencies for a conductor with an elliptical cross-section and for a thin strip, respectively).

Fig. 6 shows the normalised transport ac losses Q of Sample 2 in dependence on normalised current of amplitude I_0 measured by the potential wires L (see Example) (open symbols - bare tape, solid symbols - wrapped in NiFe foil). (The solid and dashed lines represent the theoretical dependencies for a conductor with an elliptical cross-section and a thin strip, respectively).

Fig. 7 shows the magnetic field lines of two parallel tapes carrying parallel (a) and antiparallel (b) currents with the same critical current density $j_c = 10^9$ A/m^2 in the fully penetrated state.

Fig. 8 shows the current-voltage characteristics of Sample 3 in increasing current, in the vicinity of an another parallel piece of the same sample, for different orientations of the currents in the tapes (see Fig. 7). (• - no covering, no current in the second tape, △ - no covering, parallel currents, ▽ - no covering, anti-parallel currents, ■ - Fe cover, no current in the second tape, ◇ - Fe cover, parallel currents, □ - Fe cover, anti-parallel currents). a) linear scale, b) log-log scale.

Fig. 9 shows the normalised transport ac losses Q of Sample 3 in dependence on normalised current of amplitude I_0 at 40 Hz. Solid symbols - no covering, open symbols - Fe covering. (○, • - current only in the measured tape, □, ■ - parallel currents, ◇, ◆ - anti-parallel currents). a) potential wires E_o, b) potential wires C, c) potential wires E_i.

Description of the Invention

An object behind this invention lies in decreasing transport ac losses in multifilamentary superconductors involving magnetic de-coupling of the filaments, by covering them with a suitable ferromagnetic material. The coefficient of decrease of losses K is directly proportional to the number of filaments. The invention can be applied to both, low-T_c and high-T_c multifilamentary superconductors. It was found theoretically that, for the filaments of circular cross-section, if the material is isotropic, there should be no I_c degradation nor ac loss increase in the superconductor caused by the presence of magnetic covering. The magnetic screening effect can be demonstrated by numerical modelling, and it was found that using magnetic materials with μ_r=100 - 200 is sufficient for effective screening. The ferromagnetic material preferably has narrow hysteretic loops to suppress the hysteretic losses in magnetic coverings and in an amount just

sufficient to achieve the screening effect. Partial screening may also effectively decrease the transport ac losses if the number of filaments is large.

In a product of the invention, the layer may be at least 0.1, 0.5 or 1 μm, e.g. up to 10, 25, 50 μm or more. The number of filaments in the product may be at least 10, 25 or 50, e.g. up to 500 or 1000 or more. Adjacent filaments may be spaced by 1 to 10 or 20 μm, or more.

By way of example, in application to (BiPb)SrCaCuO-2223 multifilamentary tapes, the choice of the magnetic material depends on the method of making such a composite. When applying the magnetic covering before the (BiPb)SrCaCuO-2223 phase formation, the choice of the magnetic material depends also on the processing conditions, so that it is not detrimental for BiSrCaCuO-2223 phase formation through its diffusion into (BiPb)SrCaCuO during the heat treatment. One method of creating the magnetic covering of the filaments, particularly in (BiPb)SrCaCuO-2223 tapes, comprises introducing oxide barriers around the filaments [10, 11] but containing a required portion of magnetic material. Magnetic screening of the filaments can also be an effective technique to reduce ac losses of the multifilamentary superconductors exposed to moderate ac or dc external magnetic fields, as e.g. in superconducting transmission cables or resistive fault current limiters. Appropriate choice of material can be made by one of ordinary skill in the art.

This effect is visualised by the numerical modelling shown in Fig. 1 performed on a model multifilamentary composite with (6+1) filaments of rectangular cross-section embedded in a ferromagnetic material with different relative magnetic permeability μ_r when only one filament (the upper left one) carries the current with critical current density j_c=1.1 x 10^8 A/m^2. The filaments are 250 μm in width and 30 μm in thickness. The thickness of the ferromagnetic layer is 5 μm. The spacing between the filaments, covered with magnetic layer, in both, horizontal and vertical directions, is 20 μm. Figure 1a shows the magnetic field lines (scale 2 x 10^{-8} Wb) in the case when the relative magnetic permeability of the ferromagnetic layers μ_r=1, i.e. when there is no magnetic screening. Figure 1b shows the magnetic field lines, on the same scale, when the relative magnetic permeability of the ferromagnetic layers μ_r=1000. Because of a non-homogeneous magnetic field, the screening effect can be characterised in terms of

magnetic field energy generated by the current-carrying filament in neighbouring filaments. It is reduced by 95% in the nearest neighbours and by 99.5% in other filaments. It was found that by decreasing μ_r of the ferromagnetic layers to μ_r=200, the reduction of the magnetic field energy in the nearest neighbouring filaments was still about 60% and about 95% in other filaments. Further decrease of μ_r down to 100 shifts these numbers to about 30% and 85%, respectively.

The invention can be applied also to YBCO thin film multifilamentary conductors (so-called coated conductors). They have parallel YBCO strips on a NiFe or Hastelloy substrate, separated by a buffer layer, because of the lower ac losses in a perpendicular magnetic field of such a configuration in comparison with a mono-layer conductor [17]. However, the shielding effect of covering such a strip structure by a ferromagnetic material can be less complete due to the presence of a non-magnetic buffer layer and/or the non-magnetic substrate. It depends also on the magnetic properties of the substrate. Fig. 2 shows a possible structure of such a coated (6+1) multifilamentary conductor having filament dimensions 8 μm x 2 μm, a buffer layer 0.5 μm thick, on a substrate 9.5 μm thick. The filaments are covered with a ferromagnetic layer 0.5 μm thick. The spacing between the neighbouring filaments, covered with ferromagnetic layer, is 1 μm. The current, of current density 10^9 A/m^2, passes only through the central filament. Fig. 2a shows the magnetic field lines (scale 6 x 10^{-10} Wb) when all the materials are non-magnetic. The relative magnetic permeability μ_r =1000 for either of the substrate (Fig. 2b) or of the magnetic cover (Fig. 2c), for the magnetic cover and the substrate (Fig. 2d), and finally for all the materials except for the superconductors, i.e. the substrate, the magnetic cover and the buffer layer (Fig. 2e). Fig. 2f presents the results when the substrate is non-magnetic, keeping the permeabilities of the buffer layer and the magnetic cover at μ_r=1000. The scale of the magnetic field lines is the same, to enable a direct comparison of the results.

The effect of the ferromagnetic properties of the substrate is large (Fig. 2b). Similarly, the effect of the magnetic cover with the non-magnetic buffer layer (Fig. 2d) greatly increases the magnetic field in the filamentary space. Making the buffer layer ferromagnetic (Fig. 2e) has a significant effect on magnetic screening of the filaments. The magnetic field in neighbouring filaments generated by the current in the central

filament, expressed again in terms of magnetic field energy, is suppressed by about 99.6 % in comparison with the case when all the materials are non-magnetic (Fig. 2a). A similar screening effect is obtained also when the substrate is non-magnetic and the permeabilities of the buffer layer and the magnetic cover are at μ_r=1000 (Fig. 2f). Setting the value of μ_r=100 still gives screening of about 70 %. The magnetic screening is therefore most effective if each filament is completely embedded in a ferromagnetic material.

The effect of magnetic de-coupling of the filaments, surrounded by ferromagnetic layers, on transport ac losses of a composite can be derived theoretically. Full details have been reported [18].

It can be determined that results for a current-carrying superconducting cylinder of an elliptical cross-section embedded in a ferromagnetic space differ significantly from those derived for an infinitely thin strip placed either between two perpendicular ferromagnetic half-spaces or in an open-curved convex cavity in ferromagnetic space [19, 20]. In these cases, a strong current redistribution in a magnetic field-free region of the strip was found, leading to a large enhancement of the total loss-free current. However, besides the problem of validity of that one-dimensional critical state model, the problem of finite size of such ferromagnetic geometries as well as the screening of the magnetic fields of neighbouring filaments has to be solved.

In summary, for a superconductor having a circular cross-section, the presence of a magnetic surrounding does not influence the magnetic field distribution within the superconductor nor the transport ac losses. For a superconductor having an elliptical cross-section, the magnetic surrounding significantly affects both the magnetic field distribution and the transport ac losses. However, the theoretical analysis was made only for the simplest critical state model with j_c=const and in a fully penetrated state. In standard (BiPb)SrCaCuO-2223 tapes, the individual filaments typically cannot have a circular cross-section because of poor alignment of the grains and texture, resulting in low j_c values. The filaments must have approximately elliptical cross-sections, e.g. having an aspect ratio of about 10. Their critical current densities appeared to be very sensitive to the magnetic field and also to its orientation with respect to the width of the filaments. Nonetheless, it is possible to determine experimentally the behaviour of (BiPb)SrCaCuO-

2223 filaments in the presence of a magnetic covering.

Besides the transport ac losses in superconducting filaments, there are some additional losses in their magnetic coverings, which are basically hysteretic in nature. They depend on the particular ferromagnetic material used and on the form of its hysteretic loop at given frequency of the transport current. Preferably, the ferromagnetic material has a very narrow hysteretic loop.

Fig. 3 shows two typical hysteretic loops, of a soft iron and a ferrite, which can be considered as suitable candidates for magnetic coverings. To estimate the orders of magnitude of the magnetic fields on the surface of the superconducting filaments, to which the magnetic covers will be exposed, a single filament with a circular cross-section of radius R may be considered. The tangential magnetic field component H_t on its surface is given by

$$H_t = \frac{I}{2\pi R} = \frac{jR}{2} \qquad (1)$$

where I is the current and j is the current density. The magnetic field on the surface of the filament is directly proportional to the current density and to the radius of the filament. For a filament having a rectangular cross-section, a similar relation is approximately valid, i.e.

$$H_t = \frac{I}{2(a+b)} = \frac{jab}{2(a+b)} \qquad (2)$$

where a, b are the width and the thickness of the rectangle, respectively. For a highly "aspected" rectangle, i.e. in the limit of a>>b, the following applies

$$H_t = \frac{jb}{2} \qquad (3)$$

By way of example, for a (BiPb)SrCaCuO-2223 tape with 55 filaments and a typical critical current I_c=45A, the magnetic field on the surface of an individual filament, without the influence of the magnetic fields generated by the neighbouring filaments, may be estimated. The real dimensions of a filament in such a tape are a≅250μm and b≅30μm, and at the critical current each filament carries a current I≅0.8 A. From (2), one obtains H_t≅1400 A/m on the surface of an isolated filament. For a thinner filament, this field will be lower. In the case of a multifilamentary tape, the magnetic field on the surface of an individual filament is a superposition of its self-magnetic field, given by equations (1) - (3), and the fields generated by the neighbouring filaments. These fields compensate each other, because the currents in all filaments flow in the same direction. Thus, an effective field, to which the magnetic surrounding of the filament will be exposed to, will be significantly lower than the value obtained above. This fact could be beneficial from the point of view of hysteretic losses in magnetic material, because the magnetizing cycle will follow some minor hysteretic loop.

The choice of a suitable magnetic material is governed by its hysteretic losses, basically given by the area of its hysteretic loop, and by the magnetic field of its saturation which should be higher than the maximum field in the composite. From the point of view of hysteretic losses, the amount of the magnetic material should be as small as possible (e.g. in a form of thin layers), in order to achieve the shielding effects. If the magnetic field starts to approach the saturation level of the shield material, a thicker material or a multiple shield may be used. In general, the use of multiple shields is more efficient than increasing the wall thickness. There exists a variety of magnetic materials with widely spread magnetic properties [21, 22].

Permaloy or molybdenum-permaloy powder can also be used. The effective relative permeability of these powders ranges from 5 to 550. The lower effective permeability leads to increased stability of this permeability against temperature variations and dc bias conditions. In addition to the linearity in the initial permeability region, the shearing of the hysteresis loop by the distributed air gap prevents saturation at high power levels. Special materials with different anisotropies can be prepared to have a very narrow hysteretic loop, i.e. very low hysteretic losses [23]. There exist soft magnetic materials with relative permeabilities >10 in external magnetic fields up to about 0.1 T.

Partial screening may sufficiently decrease the transport ac losses if the number of filaments is large.

Preliminary results, using iron powder as a shield on a single (BiPb)SrCaCuO-2223 tape exposed to a magnetic field generated by an another parallel (BiPb)SrCaCuO-2223 tape, showed that the screening was effective: I_c degradation was about 20 %; in the range of currents $0.5I_c$ - I_c, the loss increase was about 2.5 times, including the losses in the iron; $k(i) \leq 2.5$ at $i = 0.5$; 1 and $\alpha \cong 0.78$ for a tape with aspect ratio 14 and the thickness of the covering >> than the thickness of the tape. Using these parameters for a 55 filament tape, one obtains $K \approx 36$.

The following Example illustrates the invention.

Example

Three (BiPb)SrCaCuO-2223 tapes were tested, i.e. a 55 filament tape with AgMg sheath/Ag matrix (Sample 1), a (6+1) filament tape with Ag matrix (Sample 2) and a 55 filament tape with Ag sheath/Ag matrix (Sample 3). The magnetic cover layers were a fine Fe powder (99.5% purity) mixed with a GE varnish, 1 mm thick, applied by screen-printing (Samples 1 and 3) or a 25 μm thick NiFe foil wrapped tightly as 1 layer (Sample 2). All measurements were performed at 77 K in liquid nitrogen. Two different effects were studied, i.e. the influence of magnetic covering on critical current and transport ac losses of individual tapes, and the influence of the magnetic covering on screening properties of a tape in presence of an another current-carrying tape.

a) Influence of magnetic covering on critical currents and transport ac losses

Potential taps L, C, E were attached on different parts of the tape to measure the different types of transport ac losses. Potential wires L were in the form of an ordinary loop surrounding also the magnetic covering and so measuring the overall losses of the covered tape, i.e. the losses in the superconductor plus the losses in magnetic covering. The loop extension from the tape edge was 14 mm. The potential wires C (centre) and E (edge) passed along the surface of the tape, parallel to its axis, under the magnetic covering, in order to measure the influence of the covering on ac losses in the tape alone. It should be noted, however, that the losses measured by the potential wires C and E are only apparent losses, because of their very small loop extension [24], i.e. only the distance between the filamentary zone and the surface of the tape. The standard lock-in

technique was used for transport ac loss measurements [6, 24]. The dc current-voltage characteristics were measured by a classical 4-point method in increasing and decreasing current. Because of the hysteretic properties of both the (BiPb)SrCaCuO material and the magnetic covering, the first run of the dc current-voltage characteristic measurements differed from the subsequent runs, due to the influence of trapped magnetic field [25, 26]. The results of the subsequent runs are reported.

Fig. 4 shows the dc current-voltage characteristics at increasing (solid symbols) and decreasing (open symbols) current for Sample 1 as received, covered with screen-printed Fe powder and after removing the Fe covering. It can be seen that the Fe covering has a significant influence on the dc current-voltage characteristics. The critical current I_C determined at the electric field criterion E=1 V/cm and the n-parameters characterizing the linear slope of the current-voltage characteristic in log-log representation ($E \approx I^n$) (Fig. 4b) are given in Table 1, below. The linear slope occurred in a range of electric fields of about 0.5 - 10 μV/cm. Covering with Fe decreases both I_C and the n-values. Both I_C and the n-parameter are higher at decreasing than for increasing current. The critical current degradation caused by the Fe covering is about 22%.

Normalised transport ac losses Q of Sample 1, as received, covered with screen-printed Fe powder and after removing the Fe covering, measured by the potential wires L, C and E at 40 Hz in dependence on normalised current, are shown in Fig. 5. There is a significant difference in the losses measured by the central (C) and edge (E) potential wires (Fig. 5a). The presence of the covering does not much affect the values, but transport ac losses measured by the loop L are much higher in the presence of the Fe covering (Fig. 5b). They represent both the losses in the superconductor and the losses in the ferromagnetic covering, i.e. the overall losses. The increase of the overall normalised losses in the presence of Fe covering, in the range of normalised currents I_0/I_C=0.5 - 1, which is the range of practical interest, is by a factor of 2.5 - 2, respectively. The frequency dependence, in the range of 40 - 90 Hz, of both the losses in superconductor and in the Fe covering, is very weak; basically, both kinds of losses are hysteretic.

In the case of the (6+1) filament tape with an Ag matrix (Sample 2) wrapped in NiFe foil, I_c degradation due to the covering was similar to that of Sample 1 covered with Fe powder (Table 1), but the overall ac loss increase was much higher (Fig. 6). In the range of the currents I_o/I_c=0.5 - 1, it was more than one or even two orders of magnitude. This was caused by the rectangular shape of the B(H) characteristic of the NiFe foil (Fig. 7) and its low saturation field matching with self-field of the Sample 2 at the current I_o $0.3I_c$. Again, both kinds of losses (in superconductor and in NiFe covering) were hysteretic in the measured frequency range (40 - 90 Hz).

From these experiments, it is clear that the hysteretic losses in the magnetic covering can form a substantial part of the overall losses of the covered superconductor. This implies that in practice the amount of the covering material should be low, and that a material with high saturation field and narrow hysteretic loop should be used.

b) Screening effects of a magnetic covering

The effect of magnetic screening was tested by measuring transport ac losses in a pair of two parallel and identical (BiPb)SrCaCuO-2223 tapes (Sample 3). The distance between the tape edges was 2mm. Tape 1 was uniformly covered with a fine Fe powder mixed with GE varnish. The thickness of the covering was about 1 mm and electrically it was an insulator. Three different potential taps (E_o, C, E_i) with potential wires leading directly on the surface of the tape along its axis were attached on Tape 1 under the covering. The measurements were made in two different orientations of the currents in Tape 1 and Tape 2, i.e. parallel and anti-parallel. The two tapes were connected in series, the leads connecting the tapes were placed far away from the samples. The potential wires E_o (*o*-outer) and E_i (*i*-inner) measured the losses on the outer and inner edges of the Tape 1 relative to Tape 2, respectively, and the potential wires C measured the losses on the central part of Tape 1. Again the measured ac losses are only apparent losses, because of the very small loop extension of the potential wires [24], and they do not represent the real losses in Tape 1. However, their dependence on the orientation of the currents in Tape 1 and Tape 2 in the presence of the magnetic covering gives information about the efficiency of the magnetic screening. Without the Fe covering, the magnetic field maps in two different orientations of the currents in tapes are very different (Fig. 7). For parallel currents, the fields in the gap between the tapes compensate each other but

for anti-parallel ones they are additive. Therefore, significant differences in apparent ac losses, measured by the potential wires E_o and E_i with and without the Fe covering, are expected, because of magnetic screening.

Fig. 8 shows the effect of the orientation of the currents in two tapes on their dc current-voltage characteristics and critical currents. The Fe covering has a significant influence on the dc current-voltage characteristics. Generally both sets of the current-voltage characteristics, i.e. with and without the covering, are almost insensitive to the direction of the currents in the tapes. The only visible effect is in the case of anti-parallel currents when the sample was not covered with Fe powder. In this case, the measured voltages are slightly higher than for the parallel orientation of the currents or with the current only in the measured tape (Fig. 8a,b). It is caused by the increase of the magnetic field at the gap between the tapes in this orientation of currents (see Fig. 7b). However, this difference has little effect on the critical current determined at 1 μV/cm (see Table 1). In the presence of the Fe covering, there is no visible effect of the orientation of the current on the current-voltage characteristics, which indicates that the screening is effective. Similar hysteresis of the current-voltage characteristics in increasing and decreasing currents (not shown in Fig. 8) as in the case of Sample 1 (Fig. 4) was observed at all orientations of the currents with and without the covering. The influence of the covering and the orientation of the currents in the tapes on critical current and on the steepness of the current-voltage characteristic (n-parameter, $E \approx I^n$), corresponding to the linear characteristic in log-log representation, is summarised in Table 1.

Transport ac losses measured by the potential wires E_o, E_i and C at 40 Hz and different orientations of the currents in the tapes for covered and non-covered Tape 1 are shown in Fig. 9. It can be seen that the magnetic covering has a significant screening effect. The losses measured by the potential wires positioned at the edges of the tape (E_o, E_i) are more sensitive to the directions of the currents in the tapes than those measured by the taps positioned in the centre of the tape (C) when the tape is not covered with Fe. Especially for the potential wires E_i (Fig. 9c), the scatter of the data with current only in the measured tape and with parallel and antiparallel currents is much larger without the Fe covering (solid symbols) than when the tape was covered with Fe (open symbols), which indicates the efficiency of the magnetic screening.

Using NiFe as the covering material, I_C degradation was similar to that for the iron powder but the total loss increase was more than one order of magnitude. This implies that the use of NiFe as a substrate in coated conductors can have a detrimental effect on ac losses. By contrast, iron powder was an effective screening material to decouple the tapes. Transport ac losses of magnetically screened tape were unaffected by the current in the neighbouring tape.

Table 1

Sample	$I_{c\ up}$ (A)		$I_{c\ down}$ (A)		n-value (up)		n-value (down)	
	no cover	cover	no cover	cover	no cover	cover	no cover	cover
1(single)	38.46	30.04	39.50	31.23	19.74	16.27	21.71	17.64
2(single)	9.40	7.48	9.48		8.52	8.68	8.83	
3(single)	42.71	30.93	43.58	32.50	20.45	16.24	23.60	16.04
3(double)(I-parallel)	42.91	30.82	43.81	32.55	21.36	15.52	24.17	17.28
3(double)(I-antiparallel)	42.51	30.84	43.43	31.68	22.98	16.24	23.53	14.18

The results presented above, for tapes (3.65 mm wide and 0.26 mm thick) covered with a layer of iron powder, show that the Ic degradation was about 20% due to the presence of the magnetic material. Numerical modelling of the critical current was in accordance with these experimental results. However, the degradation of Ic of a single filament (with dimensions 250 μm x 30 μm) due to the presence of the iron layer (5 μm thick) on its surface was found only to be about 1%. These differences can be understood considering the self-magnetic fields (which depend on the dimensions of the conductor at given Ic) and the non-linear B(H) characteristic of the iron. Consequently, the critical current of the multifilamentary tape with filaments covered with the iron layers was about 20% higher than Ic of the same tape but without the covering the filaments with the iron. From these results, one can conclude that the presence of a magnetic layer around each filament of a multifilamentary tape reduces its ac losses and in the same time slightly increases its critical current (i.e. its current-carrying capacity) by about 20%.

References

The following are incorporated herein by reference:

[1] J. Phys. D: Appl. Phys. 3 (1970) 1023

[2] Applied Superconductivity 2 (1997) 1437 (Inst. Phys. Ser. No. 158)

[3] Applied Superconductivity 2 (1997) 1423 (Inst. Phys. Conf. Ser. No. 158)

[4] Physica C 295 (1998) 198

[5] Phycica C 310 (1998) 6

[6] Physica C 323 (1999) 125

[7] Electr. Mater. 24 (1995) 1869

[8] Applied Superconductivity 2 (1997) 1223 (Inst. Phys. Conf. Ser. No. 158)

[9] Applied Superconductivity 2 (1997) 1389 (Inst. Phys. Conf. Ser. No. 158)

[10] Physica C 294 (1998) 71

[11] Journal of Superconductivity 11 (1998) 495

[12] Physica C 310 (1998) 182

[13] Superc. Sci. Technol. 11 (1998) 1255

[14] IEEE Trans. Appl. Supercond. 9 (1999) 2549

[15] IEEE Trans. Appl. Supercond. 9 (1999) 774

[16] Physica C 310 (1998) 187

[17] Müller *et al*, Paper presented at 4th European Conference on Applied Superconductivity (EUCAS '99) Sitges, Spain, 14-17 Sept. 1999.

[18] Physica C 334 (2000) 129

[19] Genenko *et al*, Paper presented at EUCAS '99

[20] Phys. Rev. Lett. 83 (1999) 3045

[21] Concise Encyclopedia of Magnetic & Superconducting Materials (Pergamon Press, 1992) (Jan Evetts, Editor).

[22] Ferromagnetic Materials, North - Holland Publishing Company (E. P. Wohlfarth, Editor)

[23] G. Bertotti, Hysteresis in Magnetism for Physicists, Material Scientists, and Engineers (Academic Press, 1998)

[24] Physica C 233 (1994) 203

[25] J. Appl. Phys. 80 (1996) 2311

[26] Majoros *et al*, Paper presented at EUCAS '99

CLAIMS

1. A multifilamentary superconductor comprising a layer of a magnetic material around each filament.

2. A superconductor according to claim 1, wherein the layer is 0.1 to 50 μm thick.

3. A superconductor according to claim 1 or claim 2, which comprises 10 to 1000 filaments around which the layer is provided.

4. A superconductor according to any preceding claim, wherein adjacent filaments are spaced by 1 to 20 mm.

5. A superconductor according to any preceding claim, wherein the filaments comprise Bi-2223.

6. A superconductor according to any preceding claim, wherein the magnetic material is ferromagnetic.

7. A superconductor according to any preceding claim, wherein the magnetic material comprises iron oxide powder.

8. A current-carrying device comprising a superconductor according to any preceding claim.

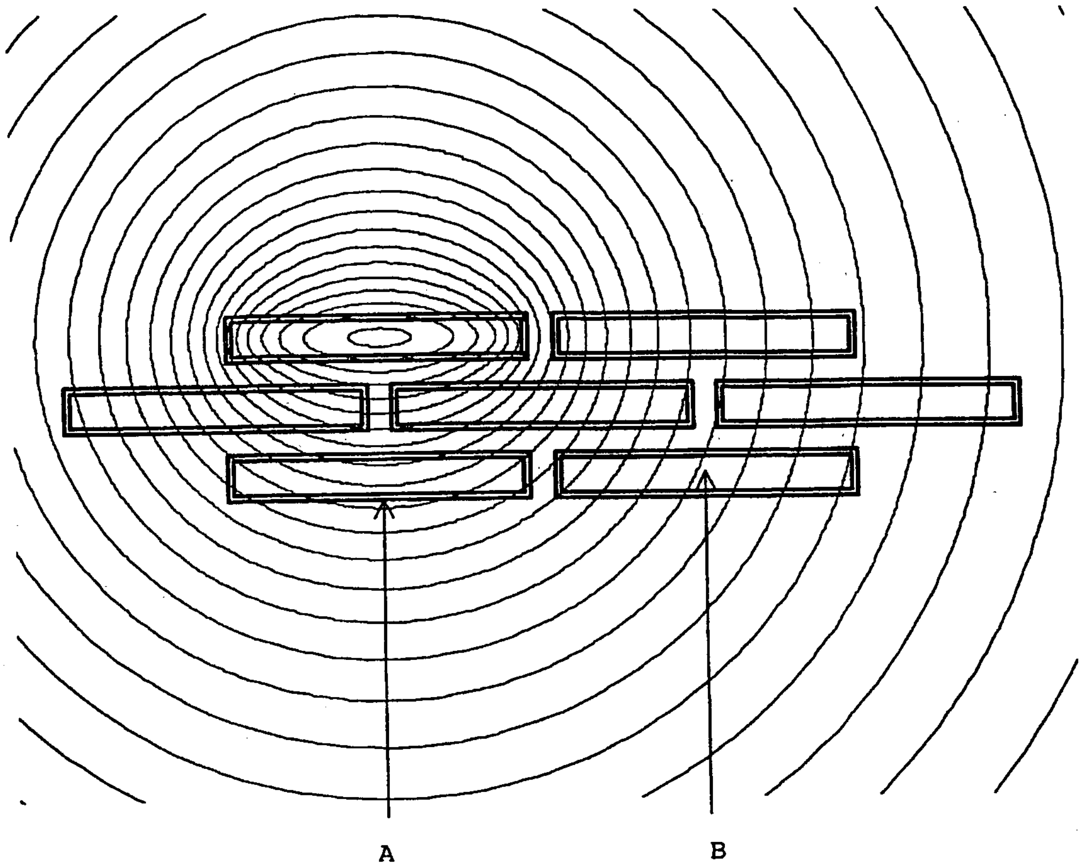


Fig. 1a

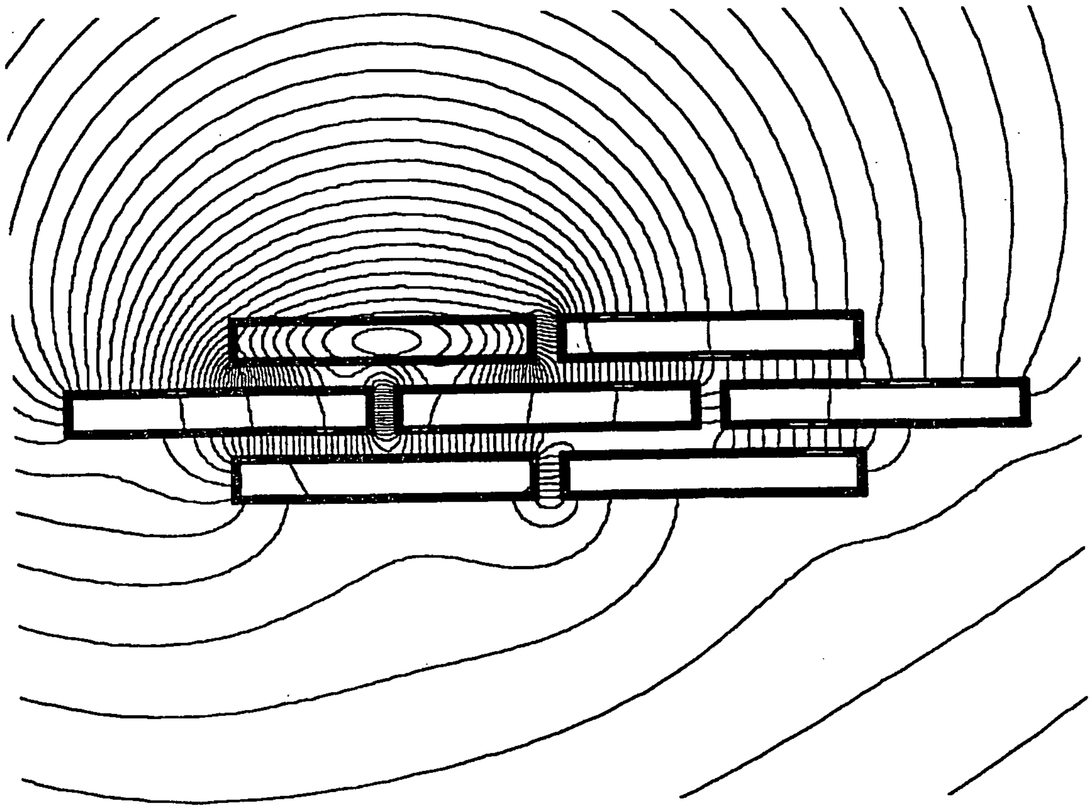


Fig. 1b

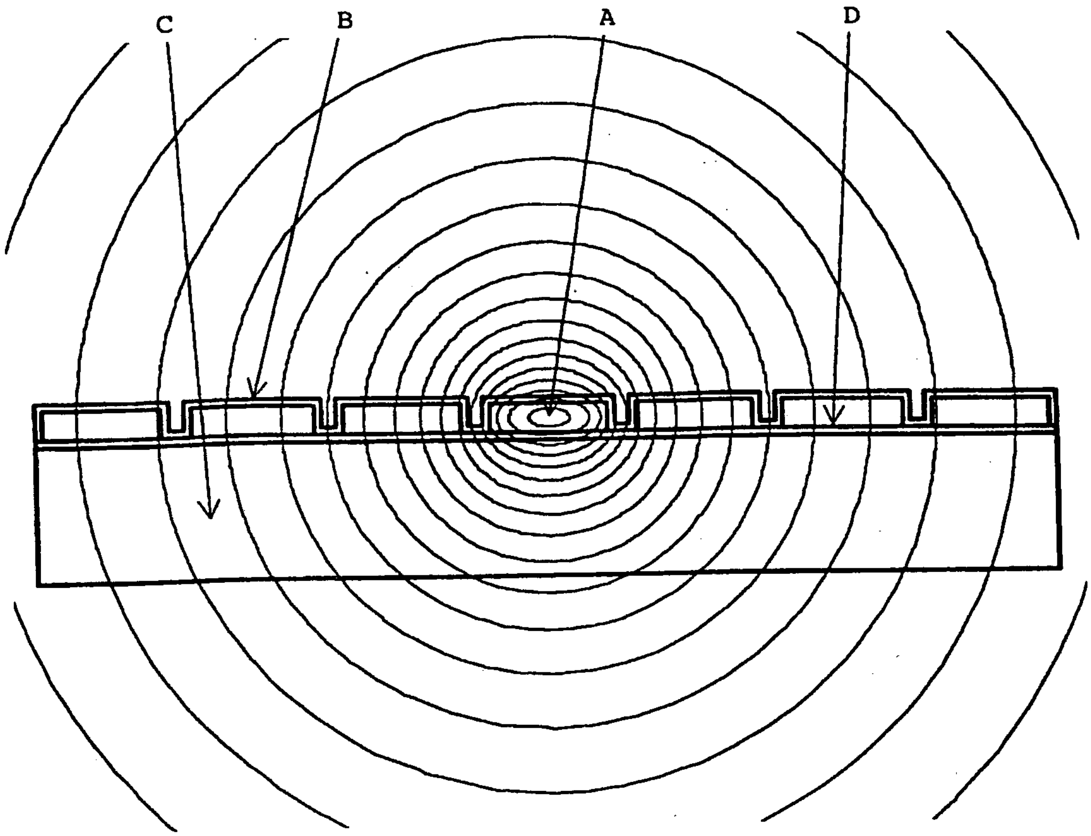


Fig. 2a

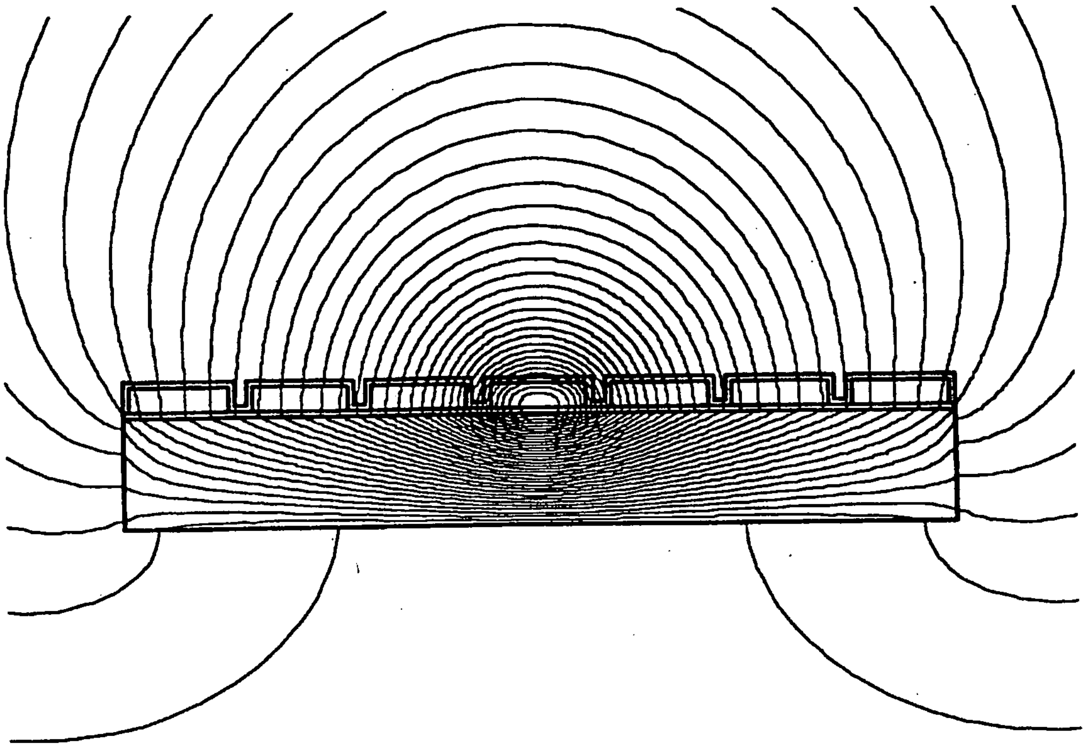


Fig. 2b

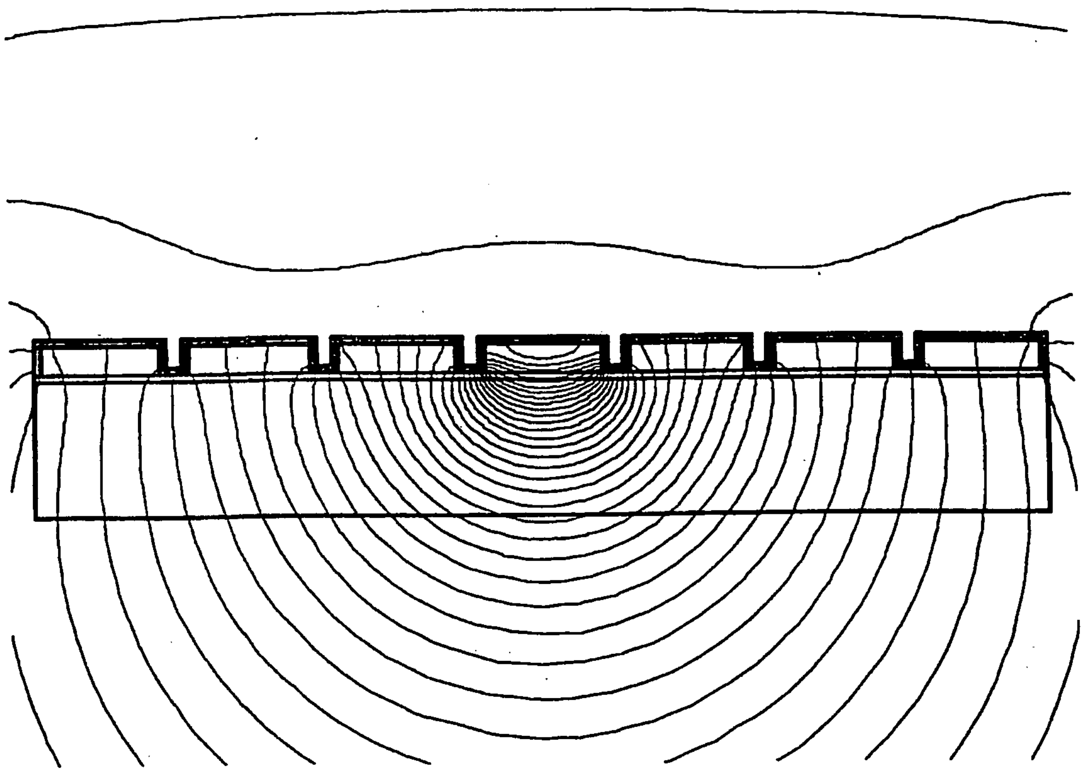


Fig. 2c

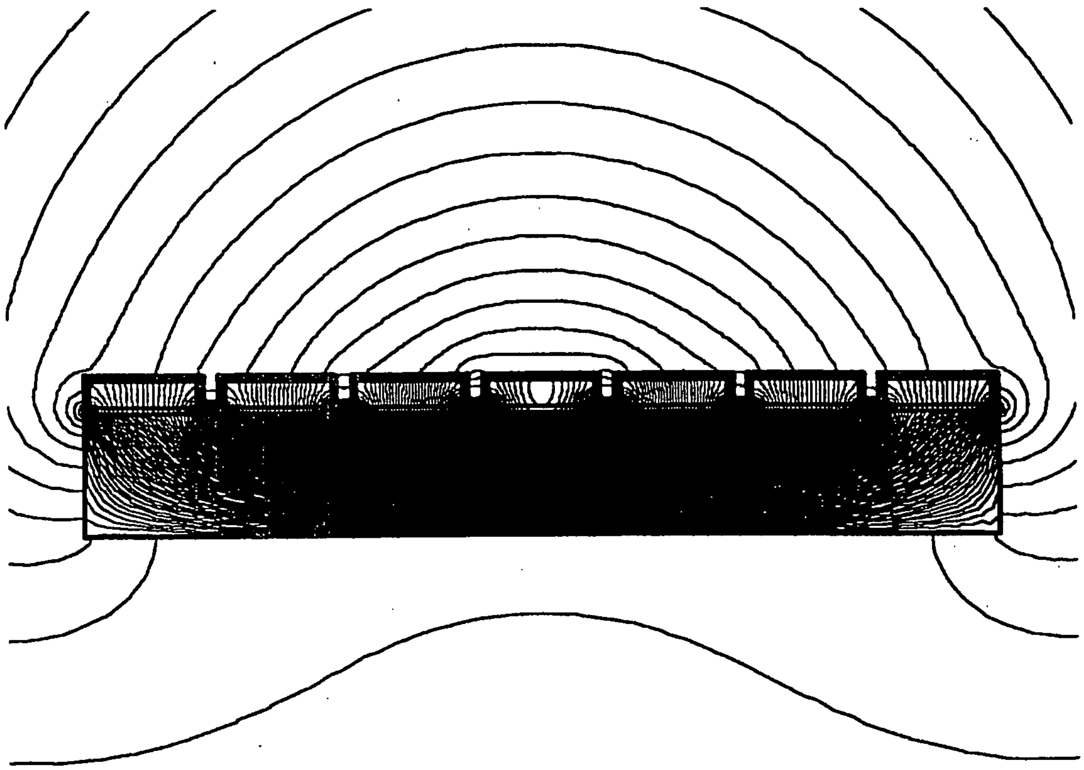


Fig. 2d

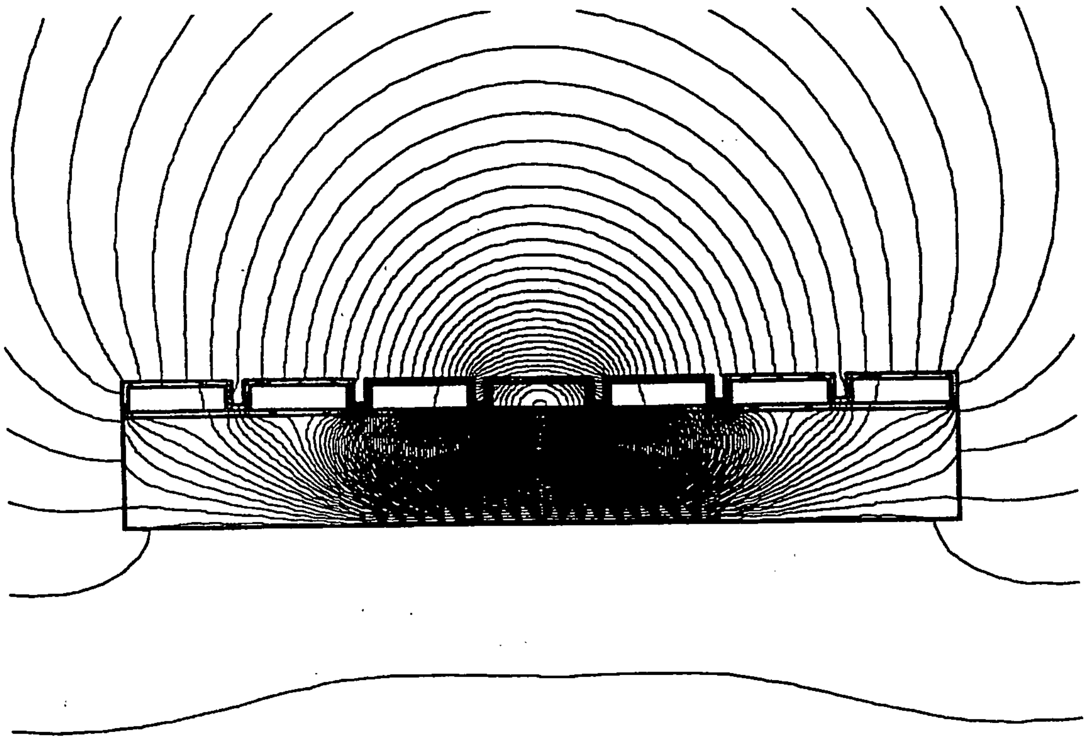


Fig. 2e

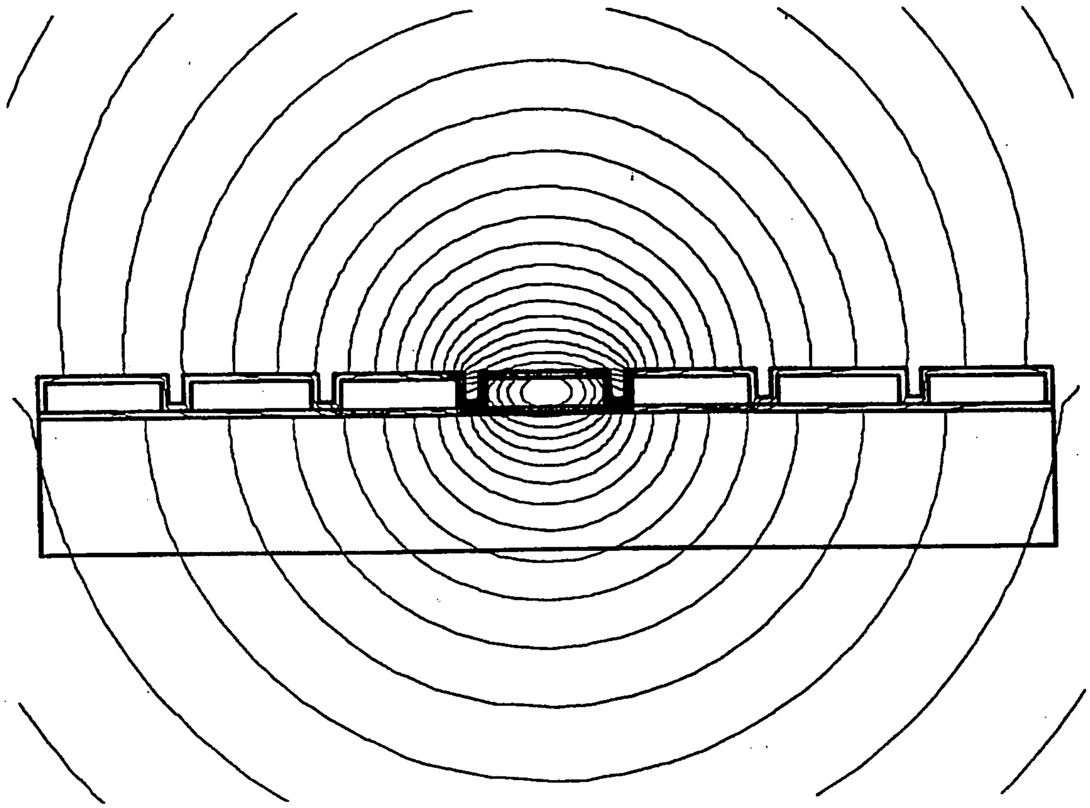


Fig. 2f

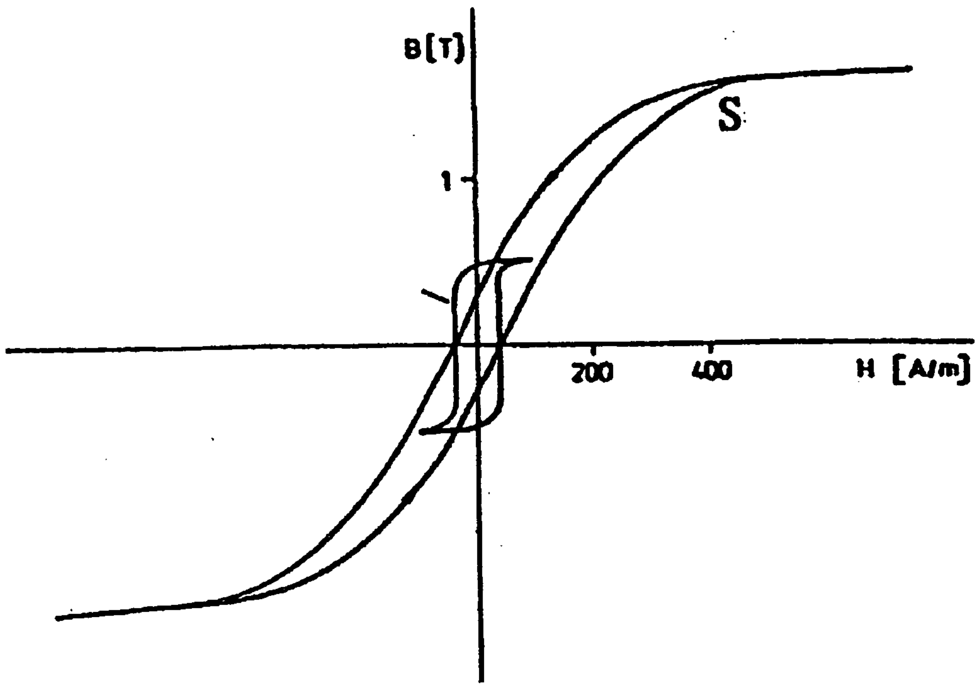
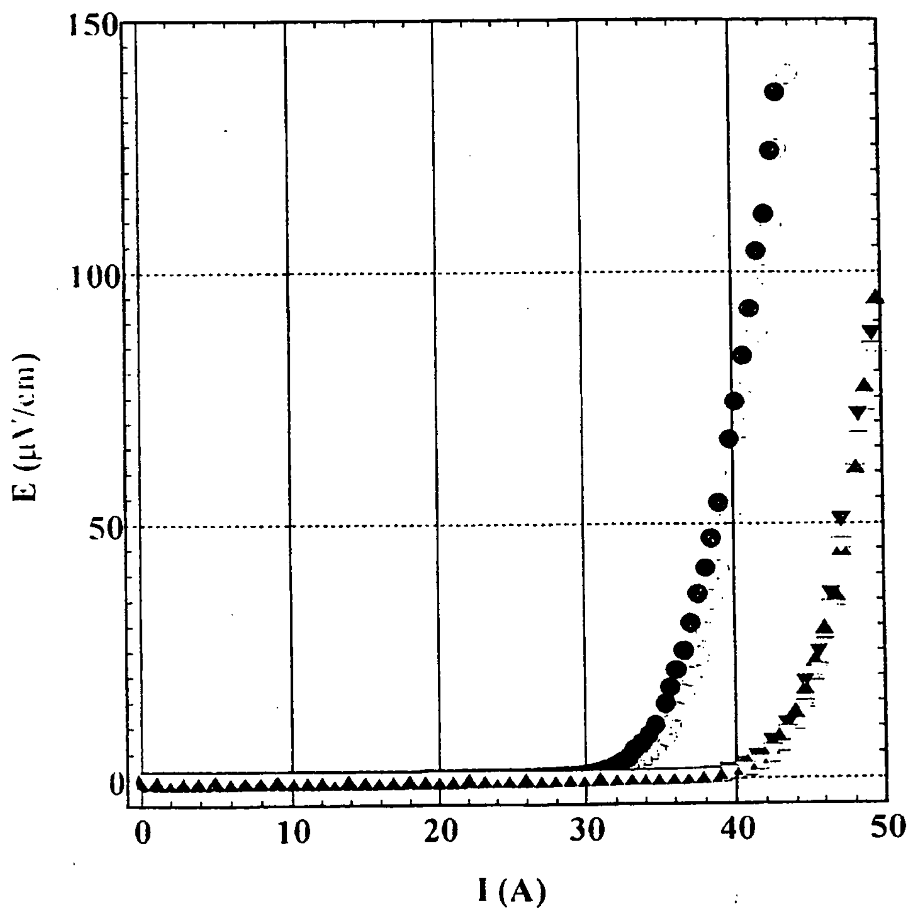


Fig. 3

Fig. 4a



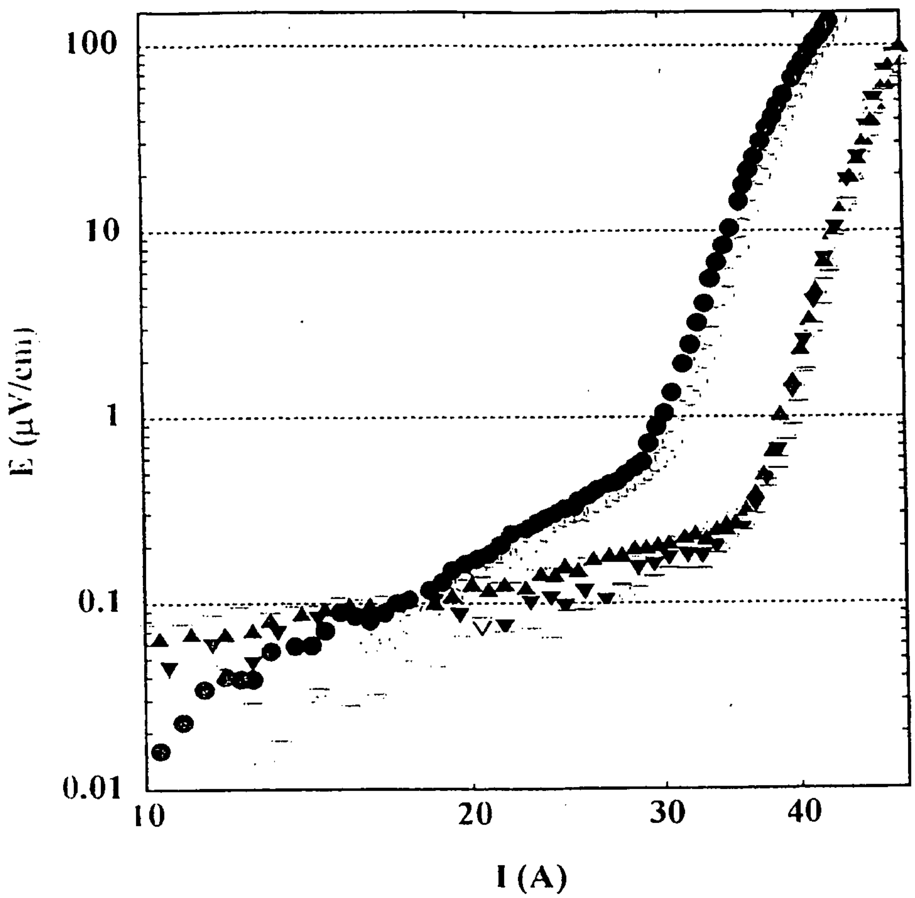


Fig. 4b

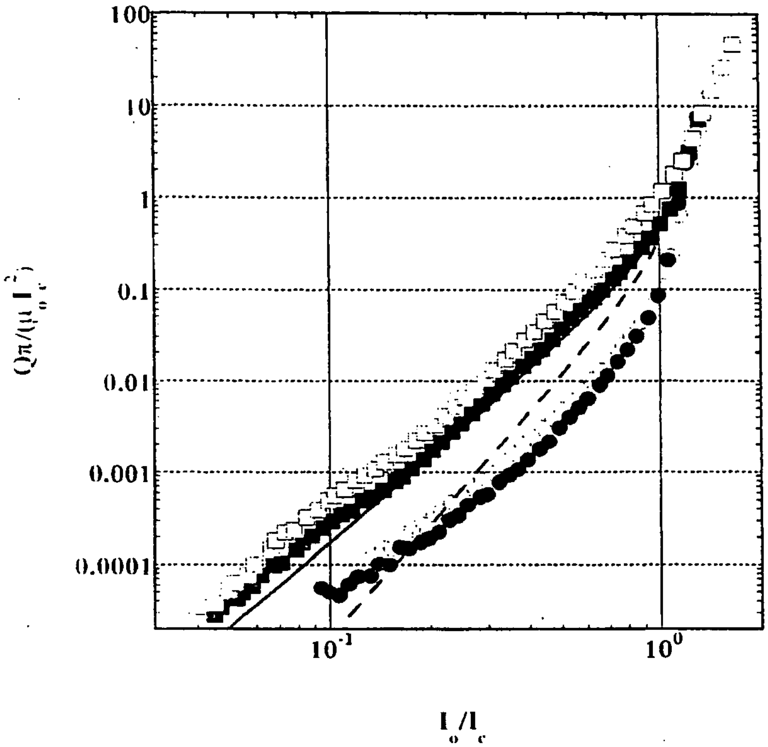


Fig. 5a

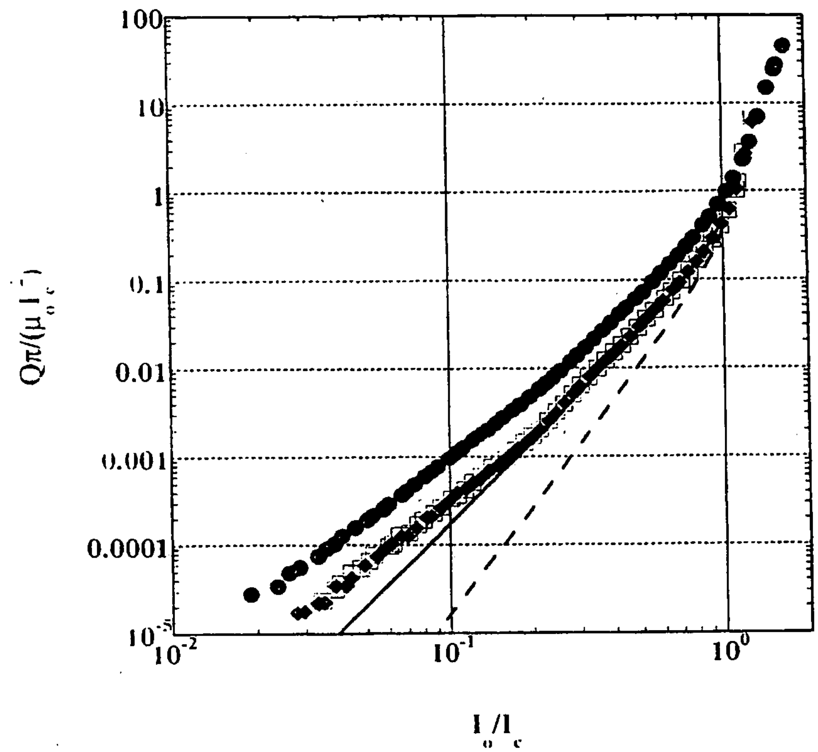


Fig. 5b

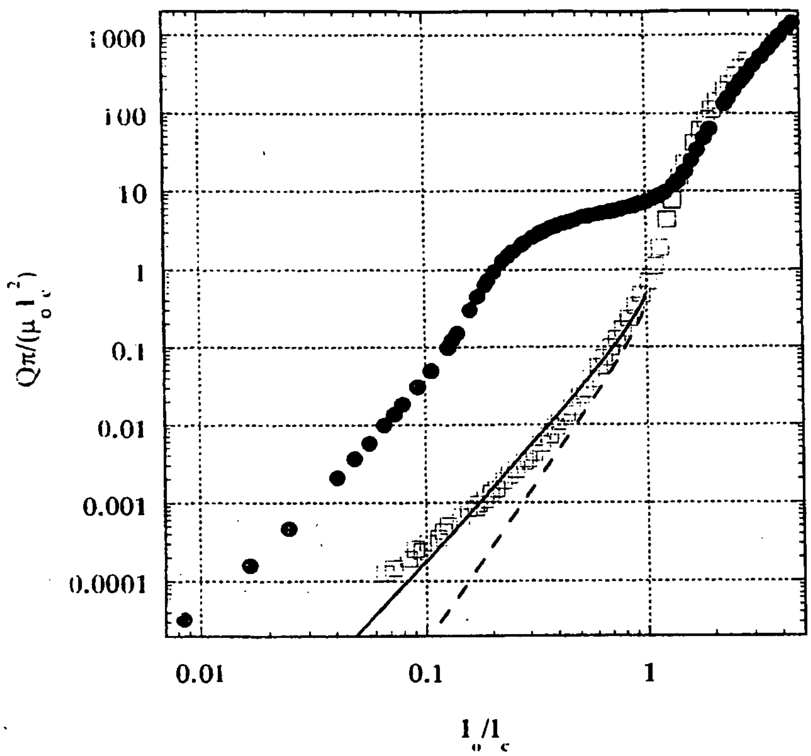


Fig. 6

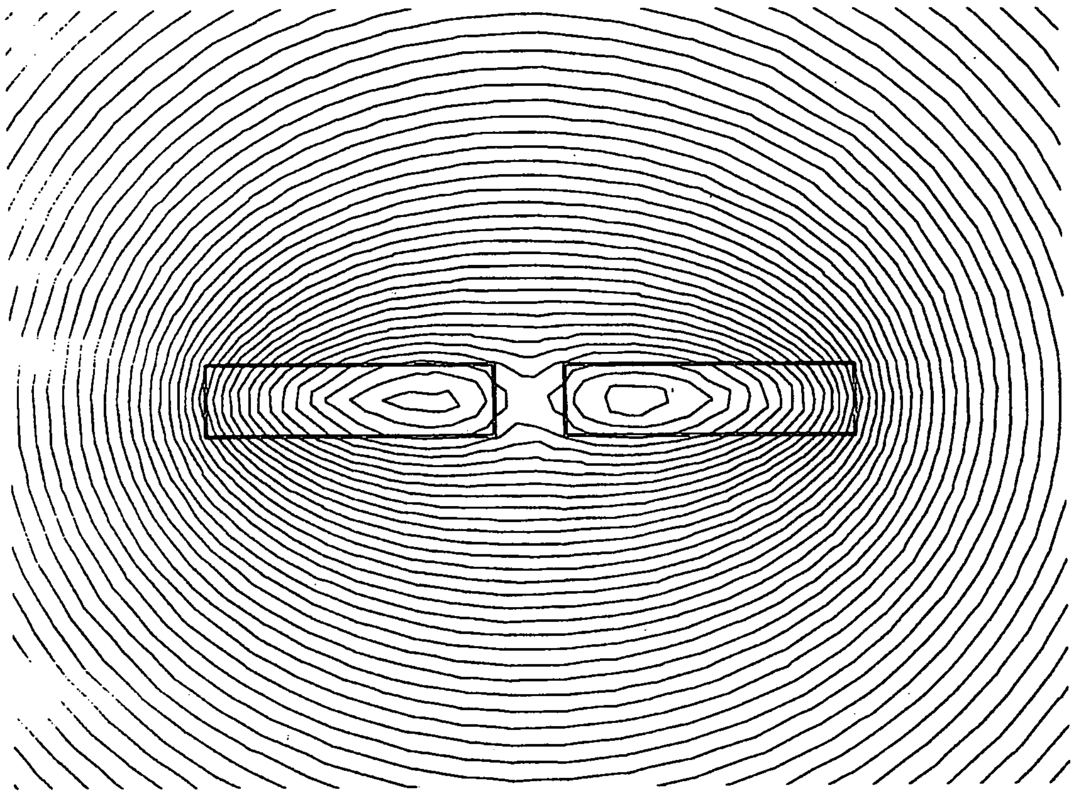
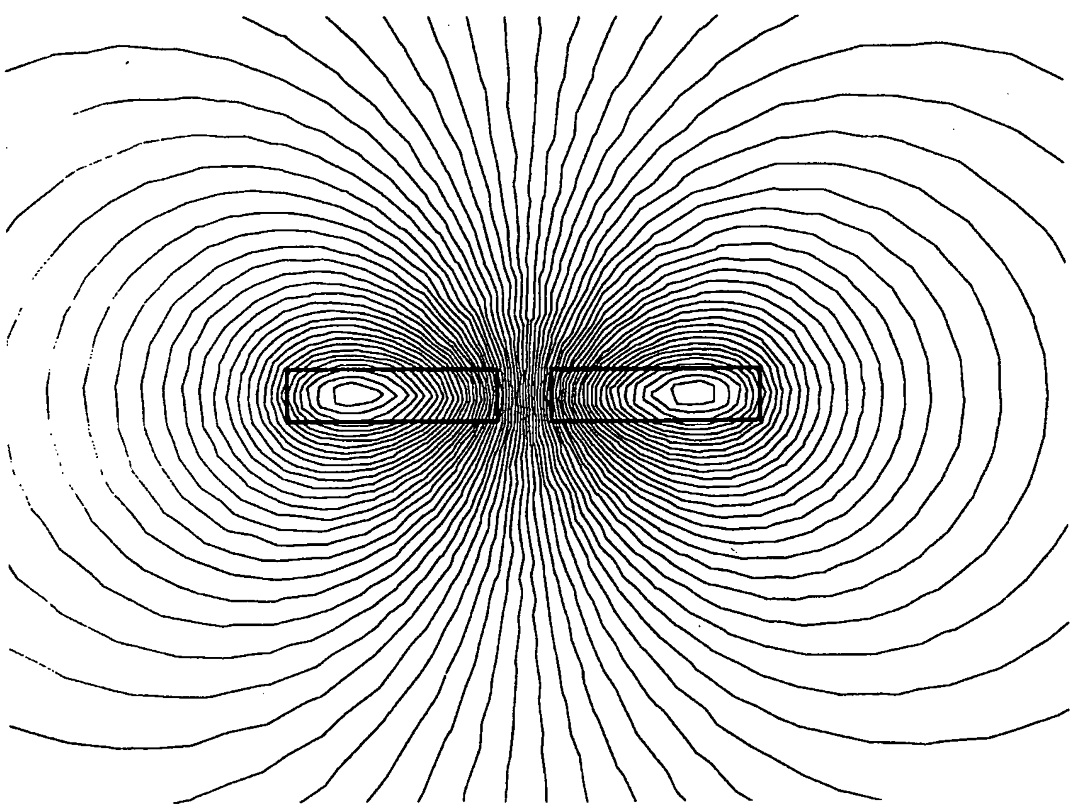


Fig. 7a

Fig. 7b



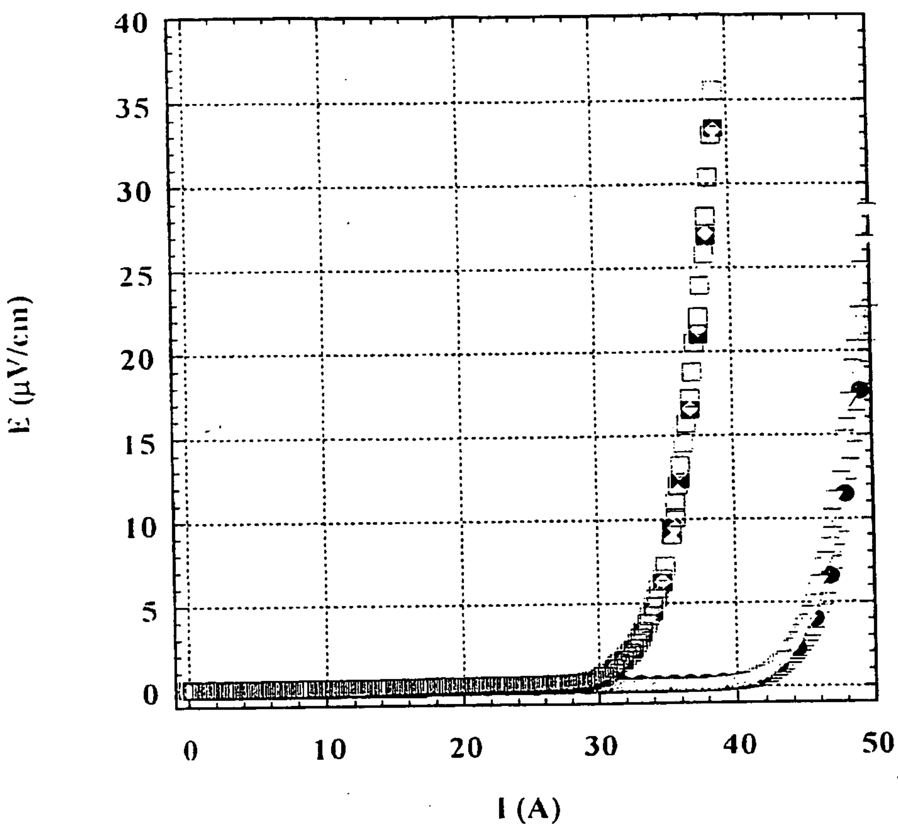


Fig. 8a

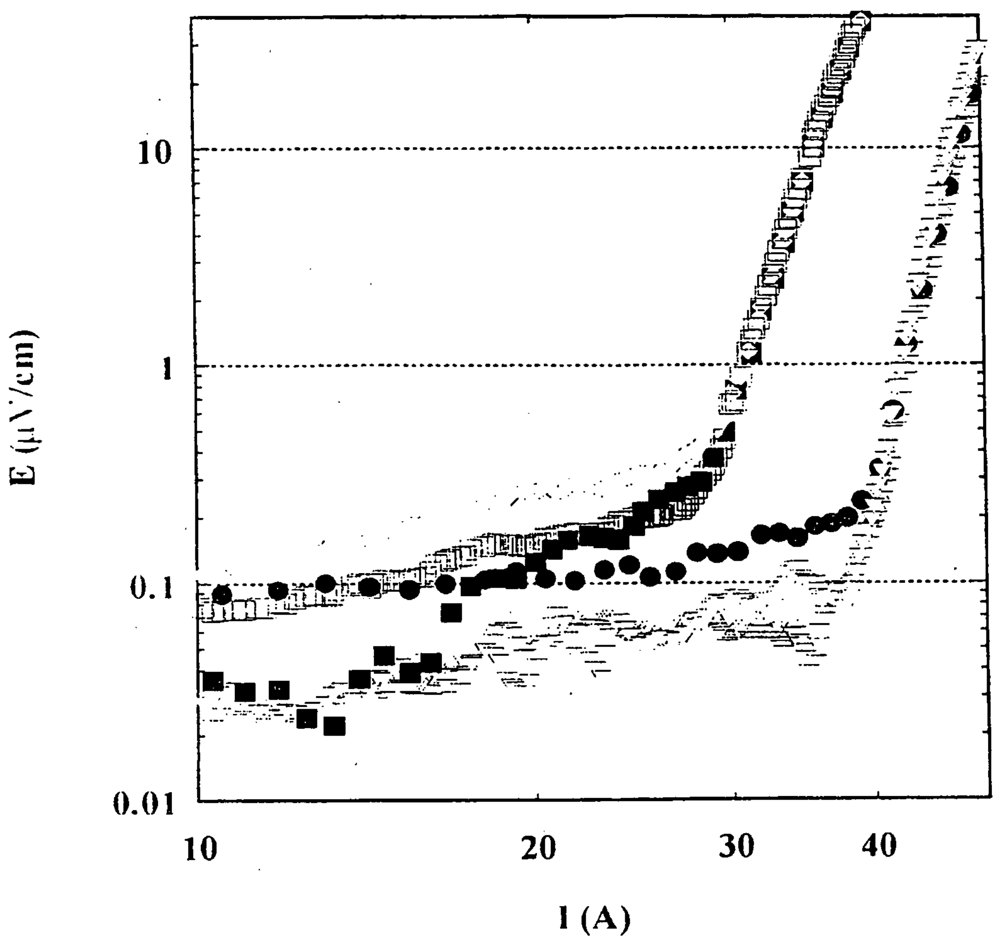


Fig. 8b

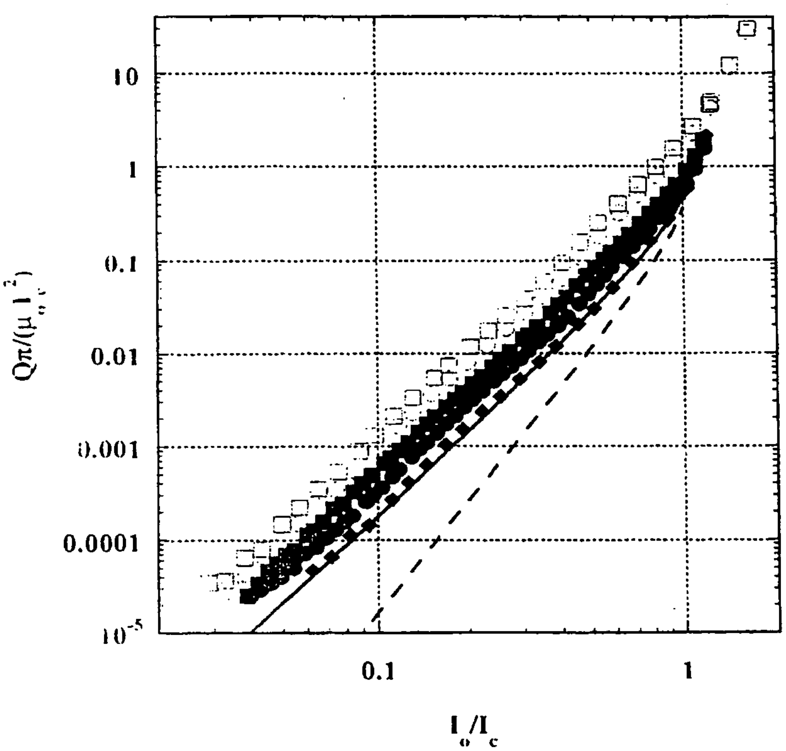


Fig. 9a

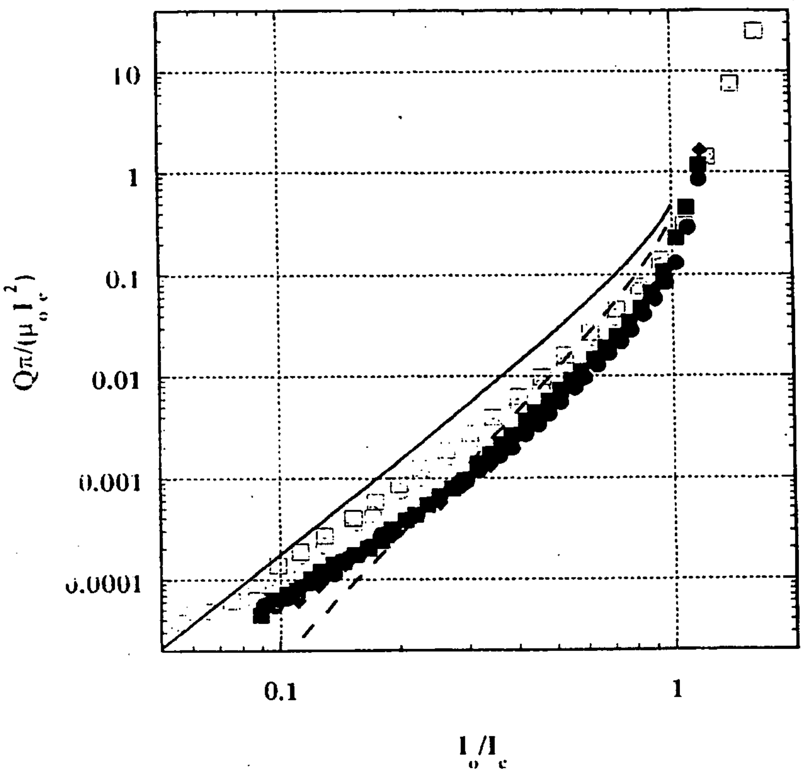


Fig. 9b

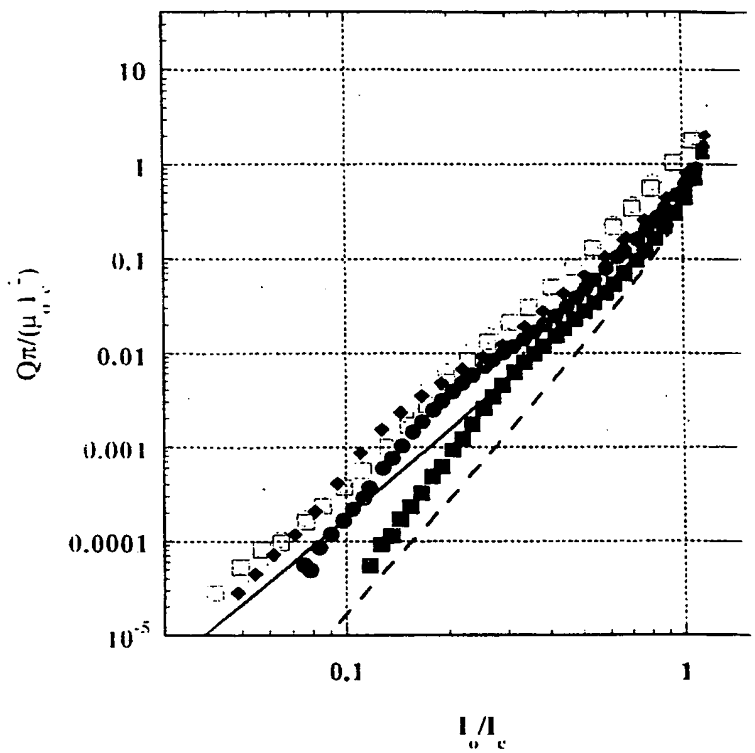


Fig. 9c

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 00/03481

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01L39/14

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

INSPEC, COMPENDEX, EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	EP 0 352 424 A (ASEA BROWN BOVERI AG) 31 January 1990 (1990-01-31) the whole document ---	1-4,6,8 7
X	PATENT ABSTRACTS OF JAPAN vol. 1996, no. 08, 30 August 1996 (1996-08-30) & JP 08 087920 A (TOSHIBA CORP), 2 April 1996 (1996-04-02) abstract ---	1-4,6,8
X	EP 0 798 749 A (SUMITOMO ELECTRIC INDUSTRIES LTD) 1 October 1997 (1997-10-01) page 5, line 48 -page 7, line 48 page 11, line 43 - line 58 figure 13 ---	1-6,8

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
24 November 2000	08/12/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Köpf, C

1

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 00/03481

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	WO 98 13859 A (AMERICAN SUPERCONDUCTOR CORP) 2 April 1998 (1998-04-02) page 9, line 25 -page 18, line 6 ---	1-8
P,X	GLOWACKI B A ET AL: "A method for decreasing transport ac losses in multifilamentary and multistrip superconductors" SUPERCONDUCTOR SCIENCE & TECHNOLOGY, vol. 13, no. 7, July 2000 (2000-07), pages 971-973, XP002153763 IOP PUBLISHING, UK ISSN: 0953-2048 the whole document -----	1-8

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/GB 00/03481

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
EP 0352424	A	31-01-1990	DE 3822684 A	11-01-1990
			DE 58908435 D	03-11-1994
			JP 2068820 A	08-03-1990
			JP 2897776 B	31-05-1999
			US 4988669 A	29-01-1991
JP 08087920	A	02-04-1996	NONE	
EP 0798749	A	01-10-1997	JP 9259660 A	03-10-1997
			US 5929000 A	27-07-1999
WO 9813859	A	02-04-1998	AU 4283297 A	02-04-1998
			AU 5079398 A	17-04-1998
			EP 1021840 A	26-07-2000